SLR2000: AN INEXPENSIVE, FULLY AUTOMATED, EYESAFE SATELLITE LASER RANGING SYSTEM

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ABSTRACT

SLR2000 is an autonomous, unmanned satellite laser ranging station with an expected single shot range precision of about one centimeter and a normal point precision better than 3 mm. The system will provide continuous 24 hour tracking coverage and reduce capitalization, operating and maintenance costs by an order of magnitude relative to current outlays. Computer simulations have predicted a daylight tracking capability to GPS and lower satellites with telescope apertures under 50 cm and have demonstrated the ability of our current autotracking algorithm to extract mean signal strengths as small as 0.0001 photoelectrons per pulse from noise.

The dominant cost driver in present SLR systems is the onsite and central infrastructure manpower required to operate the system, to service and maintain the complex subsystems (most notably the laser), and to ensure that the transmitted laser beam is not a hazard to onsite personnel or overflying aircraft. In designing the SLR2000 system, preference was given to simple hardware over complex, to commercially available hardware over custom, and to passive techniques over active resulting in the prototype design described here. This general approach should allow long intervals between maintenance visits and the "outsourcing" of key central engineering functions on an "as needed" basis. In unassembled "kit" form, the per system hardware costs for SLR2000 are expected to be less than $300K. A fully assembled and tested field system should be reproducible for about $500K per system in quantities of eight or more.

SLR2000 consists of seven major subsystems: (1) Time and Frequency Reference Unit; (2) Optical Head; (3) Tracking Mount;(4) Correlation Range Receiver; (5) Meteorological Station; (6) Environmental Shelter with Azimuth Tracking Dome; and (7) System Controller. The Optical Head in turn consists of a 40 cm aperture telescope and associated transmit/receive optics, a Q-switched microlaser operating at 2KHz, a start detector, a quadrant stop detector, a CCD camera for automated star calibrations, and spectral and spatial filters. The current design status of each of these subsystems is addressed in the present paper.

1. INTRODUCTION

The feasibility of a fully autonomous, satellite laser ranging system operating at visible wavelengths with eyesafe energies (on the order of 100 μJ for a 30 to 40 cm telescope aperture) and high repetition rates (on the order of 2 KHZ) was first postulated by Degnan[1], and some early concepts and analyses were described at the last SLR Workshop in Canberra [2,3]. The present paper gives a progress report on the engineering design of the overall SLR2000 system, while four companion papers in these proceedings describe in more detail the microlaser transmitter[4], the correlation range receiver algorithms and analysis [5], the results of recent system simulations [6], and the feasibility of SLR2000 ranging over interplanetary distances to an asynchronous laser transponder incorporating many of the SLR2000 subsystems [7]. The simulations, which are based on realistic models of the hardware and atmospheric channel, suggest that ranging to GPS in daylight is feasible with a telescope aperture as small as 40 cm[5,6].

When designing an autonomous and inexpensive system such as SLR2000, it is necessary to make certain assumptions regarding the environment into which it will be placed. Specifying an environment which is unrealistically isolated and forbidding will only drive up the fabrication and operational costs. The typical SLR2000 site is anticipated to have: (1) generally good weather and visibility; (2) good site stability with access to bedrock; and (3) easy access to basic services such as stable commercial power, communications (telephone, Internet), transportation (airports), "industrial level" security (i.e. limited personnel access), and janitorial/custodial services.

To keep construction and maintenance costs at a minimum, we have also adopted the following design philosophies:

(1) Use off the shelf commercial components wherever possible; this allows rapid component replacement and "outsourcing" of engineering support;

(2) Use TLRS-size telescopes; this constrains the cost of the optical tracking mount and telescope;

(3) For low maintenance and failsafe reliability, use passive techniques and components rather than active ones (e.g. eyesafe beams vs active radars, passive T/R switches, passively Q-switched lasers and passive multipass amplifiers).

Adherence to these fundamental assumptions and design philosophies have led to the SLR2000 design described here.

2. MAJOR SUBSYSTEMS

SLR2000 is composed of the following seven major subsystems:

Time and Frequency Reference Unit
Optical Head
Tracking Mount
Correlation Range Receiver
Meteorological Station
Environmental Shelter with Azimuth Tracking Dome
System Controller

In the following subsections, the status of each subsystem will be described.

2.1 Time and Frequency Reference Unit

The Hewlett Packard Model HP58503A GPS Time and Frequency Reference Receiver has been selected to serve as the station clock and frequency reference. The unit consists of a GPS-disciplined Quartz crystal oscillator and provides clock outputs at both 1 Hz and 10 MHz.

The one pps output has a pulse-to-pulse jitter of less than 750 psec with only one GPS satellite in view. Its time accuracy, when locked to GPS, is specified at less than 110 nsec with respect to UTC (i.e. the master clock at the US Naval Observatory in Washington, DC). In the prolonged absence of a GPS signal (unlocked), the accumulated time error is less than 8.6 μsec in 24 hours. The 10 MHz output has a Root Allen Variance, when locked to GPS, of 1.5 x 10^{-11} for a 100 msec sample time typical of artificial satellite laser ranging. Thus, ranging errors introduced by variations in the clock frequency will be submillimeter for all satellites up to and including the highest satellites, GPS, GLONASS, and ETALON.

2.2 Optical Head

The optical head consists of the telescope, a passive transmit/receive switch , a Q-switched microlaser operating at 2KHz, a start diode, a quadrant stop detector with bias supply and gating circuit, a CCD camera for automated star calibrations, and spectral and spatial filters. The outgoing single pulse energy is maximized, within eye hazard constraints, by filling the available telescope aperture with the transmit beam and by using a passive wavelength-dependent transmit/receive switch to separate the transmitted and received beams.

A block diagram of the preliminary optical head design is shown in Figure 1. A 2KHz pulse train from the Nd:YAG microlaser transmitter (21), described in a companion paper in these proceedings [4], is transmitted through a dichroic mirror (16) which passes infrared radiation at 1064 nm and reflects the frequency doubled green radiation at 532 nm. The low energy pulse train is focused by a lens (14) into a doubling crystal (15) and the resulting green radiation at 532 nm is magnified and recollimated by a second lens. After passing through a second dichroic beamsplitter (10), which is coated to pass the majority of the 532 nm radiation, a final diverging lens (8) matches the outgoing green beam to the focal length of the telescope primary for further magnification and collimation of the outgoing transmitter beam. The position of the diverging lens (8) is adjustable under computer control and can be used to correct for thermally induced variations in system focus. The outgoing reflections of the transmit beam off the two beamsplitters are used to monitor the infrared (23) and green (25) energies from the laser and doubling crystal respectively. Filter (24) blocks 1064 nm light from entering the green detector. The green radiation reflected from the satellite retraces the same optical path until it is reflected by the dichroic beamsplitter (16) into the quadrant detector (20) after first passing through a narrowband spectral filter (17), an imaging lens (18), and a variable spatial filter (19). Thus, the combination of dichroic mirror (16) and doubling crystal (15) provides a passive, wavelength-dependent transmit/receive switch [8] which is independent of polarization and allows the entire telescope primary (2) to be used simultaneously by both the transmitter and receiver.

During star calibrations, collimated starlight reflects off dichroic beamsplitter (10), passes through a broadband filter (11) centered on the 532 nm laser wavelength, and is focused by a lens (12) onto a 324 x 242 pixel Electrim Model EDC-1000M CCD array (13) which in turn measures the position of the star and provides pointing error information to the system computer for periodic mount modelling and pointing verification. It is also used to periodically check and verify accurate system focus by minimizing the star spot diameter. The star calibration optical train provides a field of view of approximately two arcminutes.

The quadrant stop detector lies behind the focal plane so that the incoming reflected laser energy and background noise is spread over the four quadrants, allowing estimation of the position of the satellite in the receiver field of view by the correlation range receiver as described in Subsection 2.4.3.

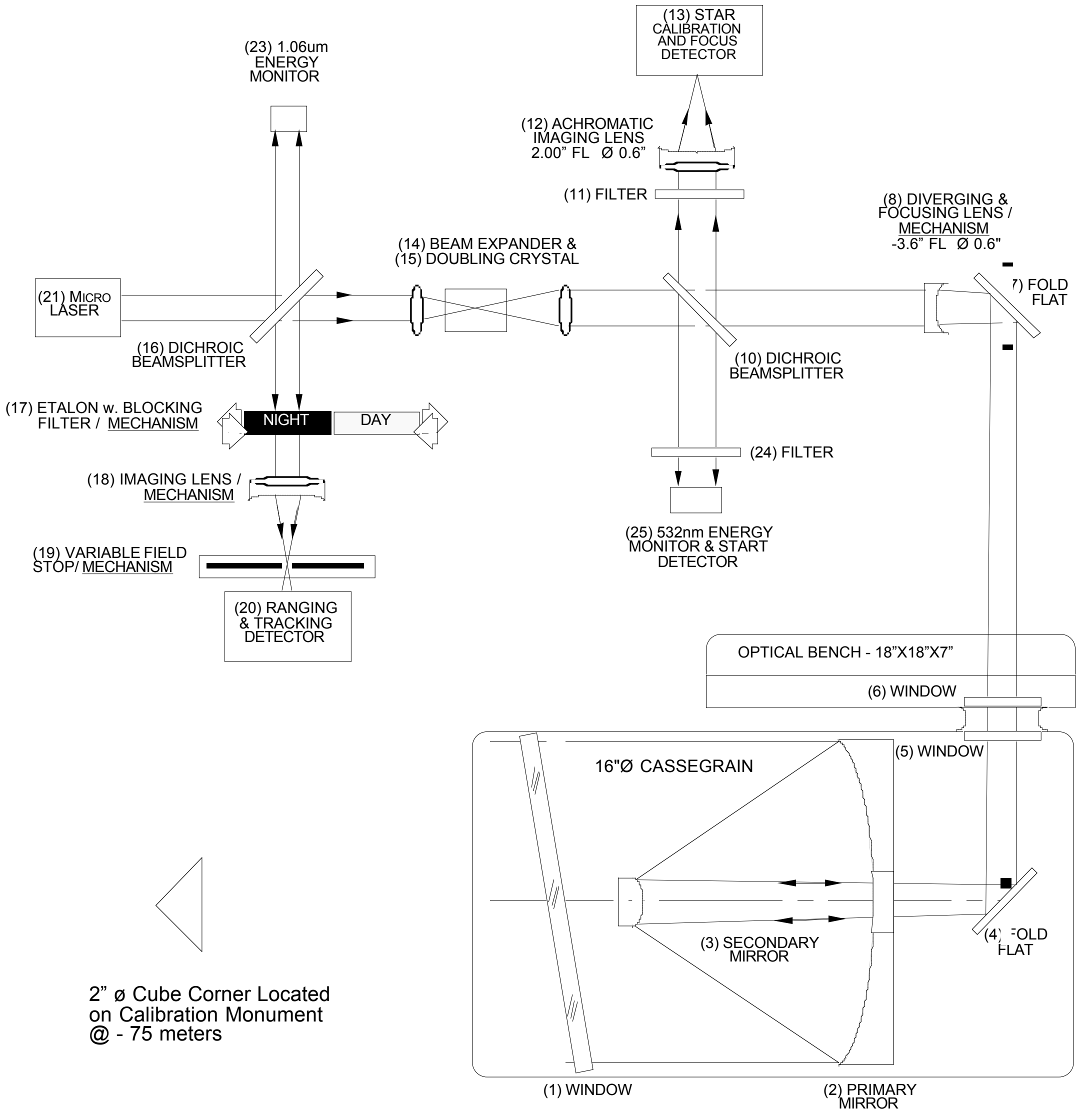

Figure 1: Preliminary block diagram of the SLR2000 optical head.

2.3 Tracking Mount

The optical head will be mounted in one of the Aerotech Model AOM360-D series of tracking mounts, to be selected upon completion of the optical head preliminary design. The latter mounts can accommodate loads up to 50 cm in diameter and are driven by direct-drive DC torque motors. The absence of gear trains and other drive mechanisms eliminates position error contributions due to mechanical hysteresis and backlash. The mount has a high axis positioning accuracy of one arcsecond, a bidirectional repeatability to one arcsecond, and a low axis wobble, also at the one arcsecond level. Orthogonality of the axes is good to 3 arcseconds, but this error can be taken out with star calibrations and mount modelling. Thermal stability is 0.4 arseconds/^{o}C. The use of Inductosyns, rather than optical encoders, for angle sensing allows electrical cables to be passed from the environmental shelter to the optical head through the center of the azimuth and elevation drive bases. The mount will be equipped with military style electrical connectors and bearing seals to provide additional environmental protection over and above that provided by the dome.

2.4 Correlation Range Receiver (CRR)

The correlation range receiver performs several critical functions which include: (1) precise time of flight (TOF) measurements; (2) the discrimination of signal from noise; and (3) the generation of subarcsecond pointing corrections. The power of the CRR is that it carries out these functions simultaneously using all of the ranging signal available to it. Like the microlaser transmitter, the CRR must operate at KHz rates. To fully understand the design and operation of the CRR, one must first describe the manner in which the TOF measurement is made under these high repetition rate conditions.

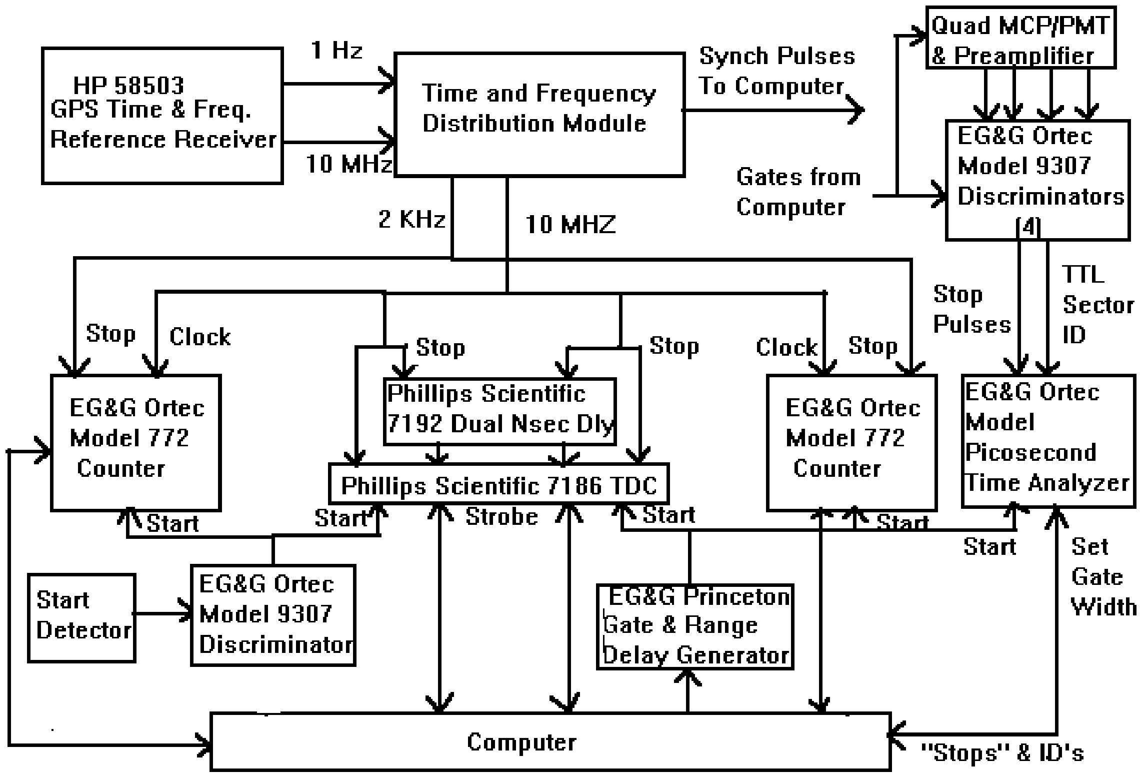

Figure 2: A correlation range receiver configuration designed using commercially available nuclear timing instrumentation.

2.4.1 CRR Time-of-Flight Measurement

Figure 2 shows a baseline design for the CRR which is built up entirely from NIM/CAMAC nuclear timing instrumentation commercially available from three companies: EG&G Ortec, EG&G Princeton and Phillips Scientific. The timing is centered around the nominal 2 KHz fire rate of the microlaser transmitter as illustrated by the timing diagram in Figure 3. The 10 MHz output of the HP Time and Frequency Reference Receiver is used to generate a 2 KHz train of synchronized clock pulses. Within each 500 μsec fire interval, there will be one "start" pulse and potentially one "stop" pulse plus noise counts. Since each fire interval corresponds to a one-way distance interval of 75 Km, the stop pulse occurring during satellite ranging in the (n+m)th interval originates from the "start" pulse occurring in some earlier (nth) interval. The (n+m)th 2 KHz clock pulse starts the "start" counter for that interval. The arrival of the (n+m)th "start" pulse stops the "start" counter and starts a time to digital converter (TDC) which is then stopped by the next 10 MHz clock pulse. Thus, the temporal position of the "start" laser pulse within the fire interval is determined by adding the "start" counter and "start" TDC vernier outputs. Similarly, the range gate from the EG&G Princeton Research Gate and Time Delay Generator starts a second "stop" counter, a second "stop" TDC, and an EG&G Model 9308 Picosecond Time Analyzer (PTA). The "stop" TDC is stopped by the next 10 MHz clock pulse and the "stop" counter is stopped by the next 2 KHz clock pulse. Adding the outputs of the second TDC vernier and the "stop" counter gives the time interval between the range gate and the (n+m+1)th 2 KHz clock pulse. The PTA is capable of recording multiple events separated by at least 50 nsec and gives the temporal positions of any signal or noise counts occurring within the range window relative to the range gate. The width of the PTA range window is programmable down to a minimum of 80 nsec. The time resolution of the PTA is the window divided by 64,000 or about 1.2 psec for its narrowest window setting. Thus, all "events" occurring within each 500 μsec fire interval are well-positioned with respect to the 2 KHz clock pulses which bound that interval.

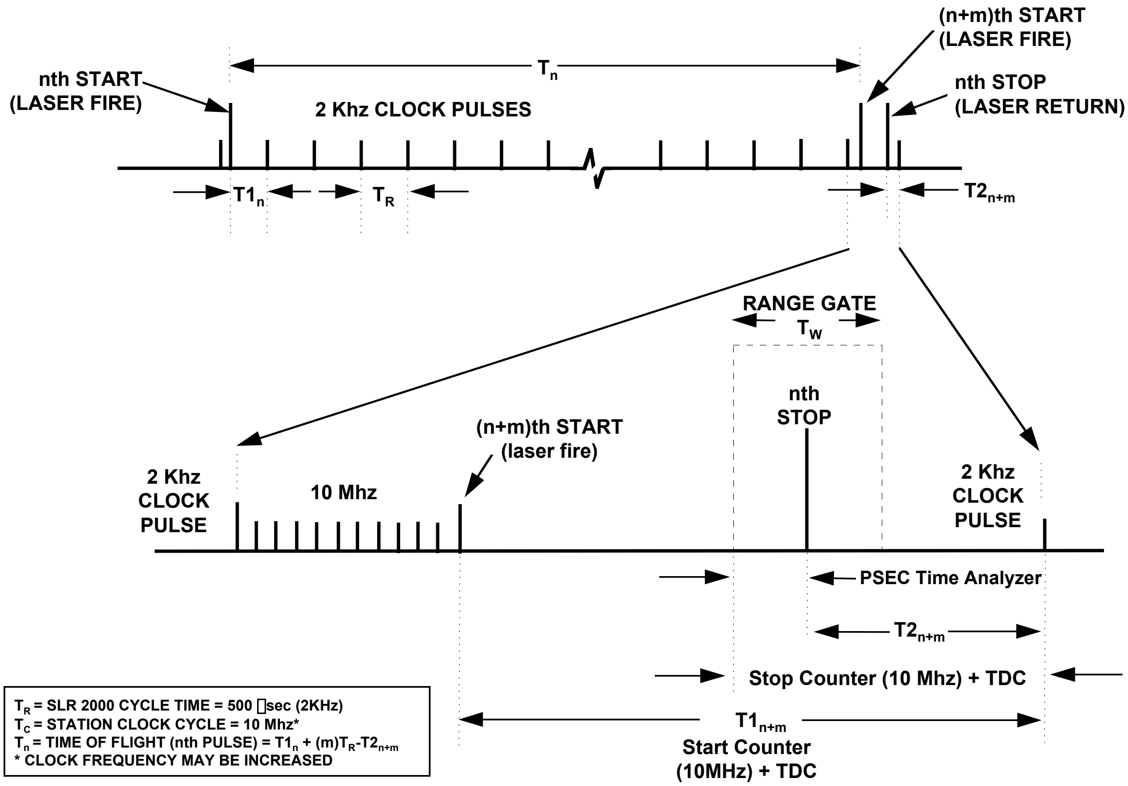

Figure 3: SLR2000 Timing Diagram

To compute the range to the satellite as measured by the nth start pulse, one must now use the following formula (see Figure 3)

$$T_n = T1_n + mT_R - T2_{n+m}$$

where $T1_n$ is the interval between the nth clock pulse and the nth start pulse as measured by the "start" counter and "start" TDC, T_R = 500 μsec is the fire interval between 2 KHz clock pulses, $T2_{n+m}$ is the interval between the (n+m)th signal arrival time and the (n+m+1)th clock pulse as measured by the "stop" counter, "stop" TDC, and PTA, and m is the number of intervening 2 KHz clock cycles between a "start" pulse and its corresponding "stop" pulse and can be computed a priori from our approximate knowledge of the station and satellite positions.

We are looking into possible enhancements which would improve the timing precision of the baseline CRR, such as multiplying the 10 MHz to higher clock frequencies (~100 MHz) or modifying the event timer developed by ATSC for the Matera Laser Ranging Observatory [9] to perform all of the CRR functions.

2.4.2 Post-Detection Poisson Filtering of CRR Range Data

The timing outputs (starts, stops, and noise events) from the CCR are transferred to the SLR2000 ranging computer which assigns them to "time bins" in accordance with satellite-dependent algorithms described in detail in [5] and simulated in [6]. Signal counts from the satellite would be bunched in a narrow time interval whereas dark current or background noise counts would be spread over the full width of the range gate. Put simply, the ranging computer looks at the number of counts in each time bin to identify the probable presence of the signal, applies an iterative filter, computes an updated range and time bias, and gradually reduces the range gate width to decrease the number of noise counts in future frames.

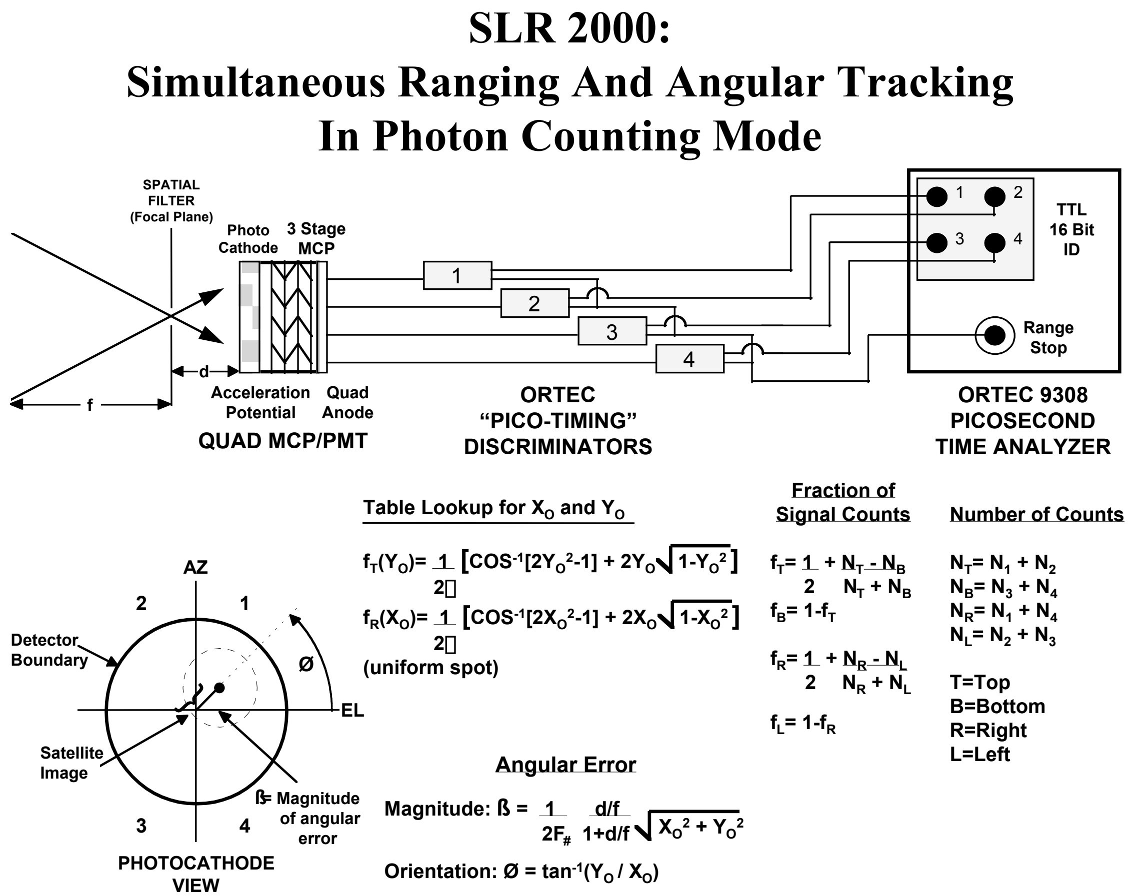

Figure 4: Correcting pointing error in the photon counting mode using the correlation range receiver.

2.4.3 CRR Derivation of Subarcsecond Pointing Error

As mentioned in Section 2.2, the stop detector is placed behind the telescope focal plane so that the satellite image is enlarged and distributed over the four quadrants as in Figure 4. Following a photon event in one of the quadrants, the corresponding anode produces an electronic pulse which is input to one of four EG&G Ortec Model 9307 "Pico-timing Discriminators". The latter device produces both a fast ECL logic "stop" pulse, which is summed with the other three discriminator channels and input to the PTA timing circuitry, and a second TTL logic pulse, which is input to a second circuit in the PTA and identifies which of the four quadrants the timing signal came from. One would expect, on average, that noise counts would be equally distributed among the four quadrants whereas, if there were a small pointing error, signal counts would pile up preferentially in one or more quadrants. Following the filtering of noise counts based on time of arrival by the postdetection Poisson filter, a subarcsecond pointing angle correction can be computed by adding or subtracting the residual counts in each quadrant using the algorithms summarized in Figure 4.

2.5 Meteorological Station

The meteorological subsystem measures pressure, temperature, and relative humidity with the requisite accuracy for millimeter ranging. In order to protect the system from the external environment and extend component lifetimes, the meteorological subsystem also monitors: (1) wind speed and direction ; (2) the presence, type, and accumulation of various forms of precipitation (rain, snow, etc.); (3) local visibility out to 50Km; and (4) cloud cover.

The meteorological station consists of four principal parts, three of which are commercially available:

(1) Paroscientific MET3-1477-001 Pressure, Temperature, and Relative Humidity Monitor

Pressure: Range 800 to 1100 mbar; Accuracy ~0.1 mbar; Stability < 0.1 mbar/year
Temperature: Range -40 to 70^{o}C; Accuracy < 0.5^{o}C; Stability < 0.1^{o}C/year
Relative Humidity: Range 0 to 100%; Accuracy $\pm$2%, Stability<1%/year

(2) Vaisala FD12P Precipitation and Visibility Sensor

The FDP12 consists of an optical transmitter, receiver, controller, and a capacitive rain sensor. It utilizes an optical forward-scatter sensor that not only sees fog but also distinguishes between precipitation particles. An ambient temperature sensor is included to increase the reliability of precipitation type assessment. The unit measures visibility optically from 10 m to 50 Km and the type, intensity, and accumulation of precipitation.

(3) Belfort 200 Wind Monitor

Wind speed is sensed by an 18 cm diameter helicoid propellor. A six pole permanent magnet attached to the shaft induces a sinusoidal AC signal in a stationary coil with a frequency proportional to the wind speed. Wind direction is sensed by rotation of the sensor on its vertical shaft Vane position is transmitted by a 10K ohm conductive potentiometer. With a reference voltage applied to the potentiometer, an analog voltage proportional to azimuth angle is produced as output.

Wind Speed: Range 0 to 135 mph; $\pm$0.6 mph
Wind Direction: Range 0 to 360^{o}; Accuracy $\pm$3^{o}

(4) Cloud Sensor

Presently we are looking at two very distinct options for detecting clouds. One approach is to add a crude lidar channel to the receiver to monitor the laser backscatter from clouds, but this requires the system dome to be open and the laser ranging system to be operating. A potentially more attractive option is to have a CCD camera outside the dome view the hemispherical sky from a convex mirror. In daylight, the sky would be viewed alternately through blue and green filters (blue sky = clear) whereas, at night, approximate cloud cover would be inferred from the presence or absence of low magnitude stars. In both cases, the image would be used in determining whether or not to open the dome, and, if partially clear, which parts of the sky should be avoided in scheduling satellite tracks.

2.6 Environmental Shelter with Azimuth Tracking Dome

The Aerotech tracking mount will be positioned (three-points of contact) and leveled, using two attached differential leveling bubbles, on a central concrete monument. A mount model, updated by frequent star calibrations, further defines and maintains the system orientation and alignment. The telescope and calibration targets will be more than 2 meters off the ground, making access by unauthorized personnel difficult.

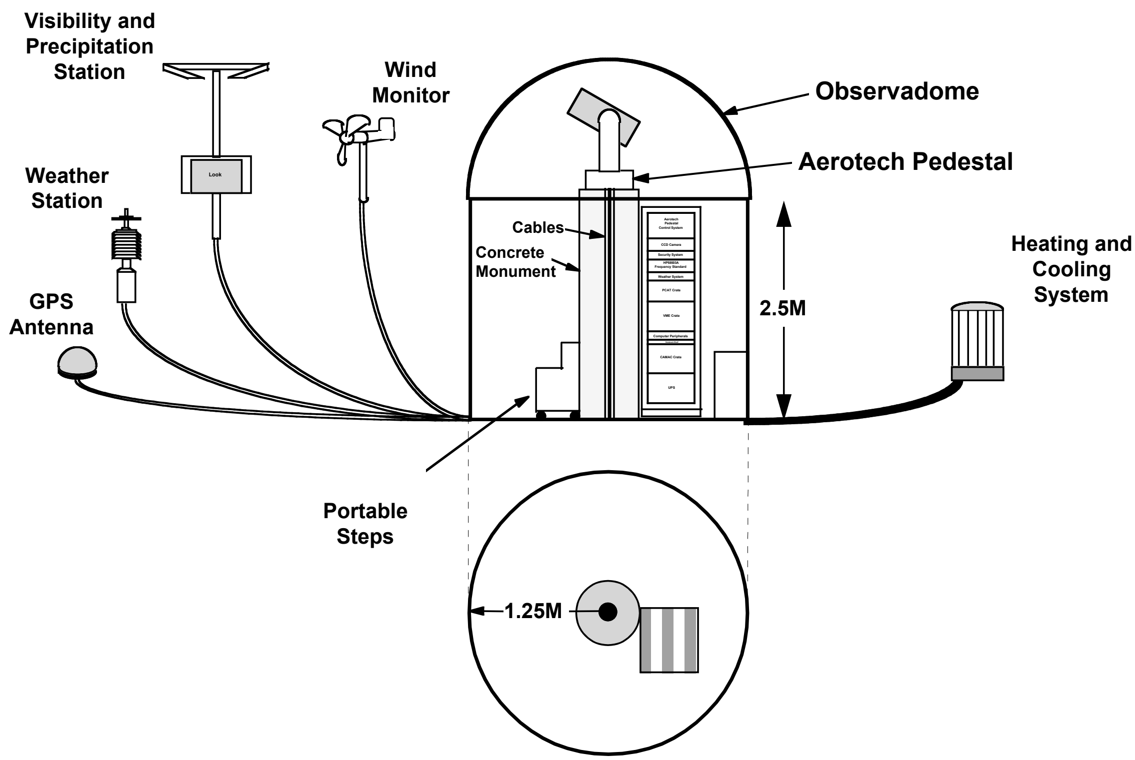

Figure 5: SLR2000 field installation concept.

The central monument sits inside an environmental shelter and a protective astronomical dome as in Figure 5. The interior of the environmental shelter is maintained at nominal room temperature (≈23^{o}C) by an external heat pump. This stabilizes the timing electronics, provides a source of heated dry air for preventing condensation on the optics, helps to stabilize the temperature of certain elements in the optical head, and provides a comfortable workplace for visiting maintenance personnel. To allow the optical head and tracking mount to follow the external ambient temperature and thereby minimize thermal gradients in the optical head during system operation, the heated (or cooled) "electronics room" is thermally isolated from the dome area by a removable "ceiling". A technician can gain access to the optical head and tracking mount by removing the "ceiling" and using a set of portable steps permanently stored in the shelter. Diagnostic tests can be performed onsite by plugging a laptop computer into the central computer system.

Internet and telephone communications are also provided in the shelter. A modem provides a backup means of communicating with the system when the Internet is inaccessible.

The 2.5 meter dome is built by Observadome™ and has a motorized slit (shutter) and azimuth drive. Both are under computer control and the dome azimuth drive is slaved to the Aerotech tracking mount azimuth.

Electrical signal and power cables are passed from the electronics rack through the center of the Aerotech azimuth stage Inductosyn , through one arm of the mount yoke, and through the elevation Inductosyn in order to power the optical head and tracking mount and to extract the ranging, star calibration, and housekeeping signals. Small hoses bearing filtered, heated (or cooled) dry air from the electronics room can also pass through the same path as necessary to prevent condensation on optics and to provide a heat exchange medium for temperature-sensitive elements in the optical head (e.g. diode pump lasers, spectral filters, etc) .

It is expected that the shelter will be equipped with additional inexpensive security devices for automatically detecting and reporting threats to system security, via Internet and/or recorded phone messages. These might include motion and intrusion sensors and surveillance cameras for detecting and reporting unauthorized personnel in the vicinity, thermal sensors for detecting heat pump failure, etc.

2.7 System Controller

The SLR2000 computer consists of three Pentium-based processors, two in a VME backplane and the third in a PC/ISA crate. The VME bus was chosen for its higher bus speed (40MB/sec), while the ISA bus was needed to handle specialized interface cards for the camera, Picosecond Time Analyzer, and mount. The ISA computer functions simply as an Input/Output processor, passing data to and from the VME computers via shared memory. The VME processors perform all of the decision making, data analysis, and external communication. One of these processors, called the "Pseudo-Operator", performs the functions of a human operator, making decisions on whether the weather permits opening the dome and tracking, which satellite should be tracked, and whether the returns in the ranging window are signal or noise. The Pseudo-Operator also monitors the system temperatures and voltages, and acts to protect the system if it detects system health or safety problems. The second VME processor, called the Analysis CPU, computes the Normal Point data from the raw tracking/ranging data and sends this data out to a central archive. This processor also gets predictions for the system, and converts it to the appropriate format. Information is communicated between the two VME processors via file and memory sharing. Both processors are expected to be running the Lynx Real-Time Operating System.

Human interaction with the SLR2000 system requires communicating with the Analysis CPU through the internet. A laptop PC running a special software package will allow personnel to monitor the operation of the system via graphical displays, get information from the system to analyze off-line, run diagnostic tests, and change system parameters.

3. SUMMARY

SLR2000 is an autonomous, unmanned satellite laser ranging station with an expected single shot range precision of about one centimeter and a normal point precision better than 3 mm. The system will provide continuous 24 hour tracking coverage for all satellites up to and including GPS and will reduce capitalization, operating and maintenance costs by an order of magnitude relative to recent outlays. The dominant cost driver in present SLR systems is the onsite and central infrastructure manpower required to operate the system, to service and maintain the complex subsystems (notably the laser), and to ensure that the transmitted laser beam is not a hazard to onsite personnel or overflying aircraft. In designing the SLR2000 system, preference was given to simple hardware over complex, to commercially available hardware over custom, and to passive techniques over active resulting in the prototype design described here. This general approach should allow long intervals between maintenance visits and the “outsourcing” of key central engineering functions on an “as needed” basis. In unassembled “kit” form, the per system hardware costs for SLR2000 are expected to be roughly $300K. A fully assembled and tested field system, including shelter and monument, should be reproducible for about $500K per system in quantities of eight or more.

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